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PROTECTION OF NONMETALLIC AIRCRAFT FROM LIGHTNING

IV - ELECTROCUTION HAZARDS FROM INDUCTIVE VOLTAGES

High Voltage Laboratory
National Bureau of Standards

NACA

WASHINGTON

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SUMMARY

Tests have been made on an XCG-7 all-wood glider and on a PT-19A training airplane having a tubular metal fuselage and wooden wings by passing electric surges simulating lightning discharges through the aircraft and measuring the voltage induced between various points which might be touched by an occupant. The metal fuselage was found to be safe, but dangerous voltages were found in the all-wood glider. A practical system of bonding supplemented by external lightning conductors is suggested which would suffice to protect the occupants from electrocution.

INTRODUCTION

A small fraction of the electric charge carried by lightning will be fatal if it passes through a vital part of the human body and an even smaller fraction may temporarily disable a pilot and cause disaster. Hence, of the many hazards involved in case a nonmetallic aircraft in flight is struck by lightning, the most immediate and obvious is the danger that the personnel may be electrocuted.

As shown in the earlier general analysis of this problem (reference 1) the quantitative evaluation of this hazard can be made by sending surge currents of known wave form through the aircraft and measuring the voltage (or current) developed electromagnetically either between points which might be spanned by the personnel or by induction within their bodies. The four obvious paths through which the surge current should be sent are (a) nose to tail, (b) wing tip to wing tip, (c) nose to wing tip, and (d) wing tip to tail. The locations where the voltage should be measured are many. Typical are seat to pedals, wheel to flap control, seat to tab control, and so forth. Estimates of the voltage induced within the bodies of the personnel by transformer action by the rapidly varying magnetic field can be computed for assumed extreme cases.

It is the purpose of this report to give the results of measurements of this type on (a) an XCG-7 all-wood glider fuselage, (b) on a PT-19A training airplane which has its fuselage formed of steel tubing. In the former case measurements were made both with and without various arrangements of supplementary lightning conductors in position.

As a basis for judging the hazards involved there is given first a discussion of the available data on the intensity of natural lightning strokes, and on the current (or charge) which may be expected to injure or seriously inconvenience the pilot.

Members of the staff of the High Voltage Laboratory of the National Bureau of Standards who contributed materially to the planning and execution of this project were Dr. F. B. Silsbee, Dr. F. M. Defandorf, Dr. F. K. Harris, Mr. J. H. Park, Mr. A. E. Peterson, Mr. E. N. Cones, Mr. H. U. Throckmorton, and Mrs. J. van Gelder. Valuable cooperation in the experiments on animals was given by Dr. G. E. Ogden of the National Institute of Health.

SYMBOLS

A amplitude of main component of lightning discharge current

A_n amplitude of nth component of lightning discharge current

a area of circuit

$\left.\begin{matrix} a_s \\ a_i \end{matrix}\right\}$ factors defined by equation (7)

C_D capacitance of skin

Ci internal capacitance of body

C_p external capacitance shunting body

C_s capacitance of glove or shoe

C_x capacitance to external objects

E voltage

e Napierian base

f frequency

I current

I_n crest value of the nth component of current

I_o instantaneous value of lightning current

I_p crest current through pilot

L_i inductance of body

L_s inductance in series with pilot

l distance from conductor to loop circuit

M mutual inductance

Q_n nth component of charge

Q_s electric charge passing through body

R_D resistance of skin

R_i internal resistance of body

t time

α_n damping coefficient of nth component

β_n frequency coefficient of nth component

γ slower damping coefficient of main component

δ faster damping coefficient of main component

φ_n phase angle of nth component

BASIS FOR SETTING SAFETY LIMITS

When a changing current I flows in a circuit which is coupled to a second circuit by having a common inductive portion, the induced voltage which appears between the extremities of the common portion is given by

$$E = M \frac{dI}{dt} \tag{1}$$

where M is the mutual inductance between the two circuits. The data given below may, therefore, be expressed either by the observed value of E for the particular dI/dt used in each experiment or by the value of M which is the ratio of these quantities and is the measure of the coupling between the main lightning circuit and the branch circuit through the pilot. To interpret an observed value of E or of M in the laboratory in terms of the hazard involved by a stroke of natural lightning, a number of factors must be considered.

First, how does the value of current and its rate of change used in the laboratory experiments compare with those to be expected in natural lightning? Second, can the voltages induced by natural lightning be resisted by a reasonable amount of insulation such as insulating pedals, boots, gloves, and so forth? Third, if such insulation is not provided (or if it proves insufficient) what current (or charge) will pass through the pilot's body? Fourth, will this current (or charge) cause serious physiological effects? Fifth, may the voltage induced in closed circuits entirely within the body cause serious harm?

Severity of Natural Lightning

It is evident from equation (1) that the induced voltage is proportional to the rate of change of current rather than to the current itself and hence that this rate of change of current is the characteristic of natural lightning which is significant in estimating the amount of insulation which would be required to protect a given person or circuit from the induced voltage. On the other hand, it will be shown that the physiological damage from electric shock seems to be most closely correlated with the maximum quantity of electricity which flows through the victim in one direction. This quantity is related more directly to the crest value of the current in the lightning stroke than to its rate of change. Data (reference 2) from various sources indicate a median value of crest current of 30,000 amperes and that a maximum of 60,000 amperes is exceeded in less than 10 percent of lightning strokes.

The best data on the rate of change of current seem to be those obtained by McEachron (reference 3) from oscillograms of 11 direct lightning strokes to the Empire State building. These data are confirmed by the results of other observers. He gets as the median value 14 kiloamperes per microsecond and as the highest observed value 36 kiloamperes per microsecond. These values are the slope of a line through points on the record at 10 percent and 90 percent of the first crest, the time to crest being about 1 microsecond on each record. Thus each value as given may be considered as the average di/dt from zero to crest of the lightning discharge. McEachron's oscillograms show that the rise was not linear and that the maximum instantaneous rate may well have been twice the average values.

The presence of the aircraft constitutes a kind of discontinuity in the path of the lightning stroke and superposed local electric oscillations may be set up in the metallic parts of the aircraft by "impulse excitation." The higher frequency component present in the laboratory surges and shown in figure 8 is presumably an example of such an oscillation. If the aircraft is equivalent to an inductance and capacitance in parallel and if the current in the main lightning stroke rises linearly and is unaffected by the aircraft, the superposed oscillation will have such an amplitude as to make the maximum momentary rate of rise of current in the inductance (that is, in the metal of the aircraft) double the maximum rate of rise of the main stroke. Thus McEachron's average values of di/dt should be multiplied by 4 to get the peak values for an aircraft in flight, giving for a median stroke 56 kiloamperes per microsecond and for the highest observed value 144 kiloamperes per microsecond.

Impedance of Circuit through Personnel

If there is no effective insulation at the points where the body of the pilot (or other person) comes into proximity with the conductors which carry the lightning current, a certain fraction of this current will be diverted through him. The magnitude of this current is to be obtained by combining the impressed crest voltage, such as was observed in the following experiments, with the impedance offered by the human body to the flow of transient currents.

For direct currents the skin (particularly if dry) offers by far the major part of the total observed resistance. When measured at low direct voltages (1 to 3 volts) the total resistance between hands ranges from 2000 to 20,000 ohms.

The electrical conduction both in the pores of the skin and in the underlying tissues is electrolytic in nature and involves the motion of molecular ions. The accumulation of these ions at the electrode and at the surfaces of various internal membranes tends to give rise to a back electromotive force of "polarization." When the time interval during which the current flows is too short to allow much diffusion of the ions, as is the case with surges and with alternating currents, the electromotive force of polarization is approximately proportional to the quantity of electricity which has passed. The relation between voltage and charge (or current) is, therefore, the same as that which characterizes a capacitor. Furthermore the outer horny layer of the skin functions as the dielectric of a capacitor the "plates" of which are the underlying tissues and the external electrodes. Measurements (reference 4) have shown that the equivalent capacitance resulting from the polarization is much the larger of these two effects. The total capacitance of the capacitor thus formed is proportional to the area of skin in contact with the external metal and may be as great as 0.4 microfarads for the palm of one hand. At a frequency of, say, 10,000 cycles the impedance of this capacitor is only 40 ohms and it, therefore, in effect "short circuits" the effective resistance of the skin. However, the internal body tissues have an appreciable resistance as well as capacitance. Measurements (references 4 to 8) show that even at 1 megacycle per second the resistance from hand to hand exceeds 500 ohms, and that the polarization in the tissues is then equivalent to the presence of a series capacitance C_s of about 100 micromicrofarads.

The principal elements of the circuit of which the pilot's body forms a part are indicated schematically in figure 1 (a). The main lightning current I_o (t) passes through the conductor B'A' and induces a voltage $M \frac{dI_o}{dt}$ into the shunting circuit which consists mostly of the pilot.

Between the handle A, which the pilot may grasp, and the junction point A', where the shunt circuit through the pilot joins the main path of the lightning stroke, there may be a few feet of cable, or a metal lever, or other conducting object, which will have a small but finite inductance. This inductance is represented by L'_s. A similar inductive element such as a pedal shank may be in the circuit at the other extremity between the pedal surface B and the junction point B'. The capacitance between the pilot's hand and the handle which he grasps (the glove serving as the dielectric) and the similar capacitance between his foot and the metal pedal (the shoe sole serving as dielectric) are represented by C'_s. The skin at each extremity is represented by the relatively large capacitance C_D shunted by the resistive path R_D through the pores. The circuit is closed through the effective series resistance R_i and capacitance C_i of the internal tissues and the inductance L_i which results from the magnetic field of the current in the body (mostly in arm and leg). The capacitance C_p is introduced to represent the small effect of the geometric capacitance directly between the arm and leg of the pilot. In addition to the foregoing there may be stray capacitances C_x to other portions of the aircraft which may be at a different potential from A or B. To take account of these last-mentioned elements would complicate the problem to an impracticable extent, and they will be ignored in the following discussion, but their presence may account for certain otherwise unexplainable effects.

This circuit can be simplified for rapidly changing transients by omitting the skin elements R_D and C_D which offer only very little impedance to a surge and by combining the series inductances L'_s and the series capacitances C'_s each into a single element L_s and C_s of figure 1 (b).

Possible Current and Charge through Personnel

The lightning stroke current in the main circuit through the coupling inductance between the junctions A' and B' may be represented in the general case as the sum of a number of components by the equation:

$$I_c(t) = A\left(e^{-\gamma t} - e^{-\delta t}\right) + \Sigma A_n e^{-\alpha_n t} \sin(\beta_n t + \varphi_n) \quad (2)$$

here the first pair of terms represent the main discharge while the summation which follows represents the superposed oscillations. The subscript n serves to identify the individual oscillatory components each of which has an initial amplitude A_n, a decrement α_n, and a frequency $f_n = \beta_n/2\pi$.

If the main surge is slightly underdamped as was the case in the laboratory tests, equation (2) can still be used by setting $A = 0$ and using one of the summation terms to represent the fundamental surge with A_n very large, about $3 \times 10^4 \text{ (sec)}^{-1}$, and with β_n not exceeding α_n.

If the main stroke current varies as shown by the first term in equation (2) it can be shown that the initial crest voltage across the capacitance C_s will be approximately given by

$$E = AM\delta \tag{3}$$

and the crest charge passing through the pilot's body will be

$$Q_s = C_s E = AM\delta C_s \tag{4}$$

For the typical case of $A = 30{,}000$ amperes, $\delta = 1 \times 10^6$; then if M is as large as 1 microhenry $E = 30{,}000$ volts and (for $C_s = 200 \times 10^{-12}$ farad) $Q_s = 6$ microcoulombs which is definitely above the threshold of feeling.

If the insulation at glove or shoe should puncture under the voltage given by reference 3 the current and charge will be decidedly larger. Assuming the insulation to fail early in the surge, the crest current through the pilot is given by

$$I_p = \frac{AM\delta}{R_1} \tag{5}$$

and the charge passing during the first swing is

$$Q_s = \frac{AM}{R_1} \tag{6}$$

For the typical values shown above and for $R_1 = 300$ ohms, these formulas give $I_p = 100$ amperes and $Q_s = 100$ microcoulombs, which might be very serious.

In general, it appears that the charge passing through the pilot will be increased, if the insulation punctures, by the factor $1/\delta C_s R_1$. For the value of C_s assumed above this is a factor of 16, although it would be less if C_s

were larger. This indicates that providing insulation at all points where the personnel might make contact with current-carrying parts would give a definite gain in protection. However, to insure such insulation at all points would introduce numerous complications, and it would seem preferable, in general, to keep the voltage low by bonding and shielding rather than to rely solely on insulation. A further consideration is that the superposed oscillations and the capacitances to other parts of the structure may contribute to the crest voltage to an extent not covered by equation (3). In fact, equation (3) should be regarded as a lower limit rather than an upper limit on the required insulation.

For the superposed oscillations of higher frequency including those excited in the aircraft members the damping factor α_n is likely to be small, β_n is larger than 10^6 $(\text{sec})^{-1}$ and A_n is small relative to the fundamental.. The higher frequency components can, therefore, be treated like sustained alternating currents by the usual symbolic method. Applying this to the circuit shown in figure 1 (b) gives as the relation between the crest value of the component I_n of the current I_i in the pilot's body and the corresponding component A_n in the main circuit.

$$I_n = A_n \left[\frac{j \beta_n M}{R_i \left(1 - \frac{C_p}{C_s} a_s\right) + \frac{j}{\beta_n C_s} \left\{a_s + \frac{C_s}{C_i} a_i - \frac{C_p}{C_i} a_s a_i\right\}} \right] \quad (7)$$

here

$$j = \sqrt{-1}$$

$$a_s = \beta_n^2 L_s C_s - 1$$

$$a_i = \beta_n^2 L_i C_i - 1$$

For components of very high frequency it is evident either from the equation or from inspection of figure 1 (b) that the capacitances function as short circuits and that C_p diverts all current from R_i. Even if C_p were zero, the inductances would predominate over the resistance R_i and the current would be

$$I_n \ (f = \infty) \ = \ \frac{A\ M}{L_s + L_i} \qquad (8)$$

The charge per half cycle would be

$$Q_n = \frac{2\ A\ M}{\beta_n\ (L_s + L_i)} \qquad (9)$$

and would become very small as β_n increased.

At frequencies not quite so high there may be certain resonance effects. The quantities a_i and a_s will each become zero at a particular value of β_n. However, even if they both vanished at the same value of β_n, the current I_n would be limited to $I_n = A_n\ \beta_n\ M/R_i$.

For some particular frequency the value of a_s will be equal to C_s/C_p and the coefficient of R_i will vanish. However, the second term will then be such as to make

$$I_n = \frac{AM\ C_p\ (C_p + C_s)}{L_s\ C_s^2}$$

The only condition which could lead to an abnormally high ratio of I_i to I_o would be to have both terms in the denominator of equation (7) approach zero at the same value of β_n. This condition would arise if

$$C_s \ll C_p \qquad (10)$$

but relation (10) is very unlikely to be satisfied. Even if it were, the chance that some important component of the stroke should have a value of β_n just right to fit the particular circuit constants and to give a dangerous resonance is very remote. Hence it may be concluded that unless the amplitude of the superposed oscillations is very large (comparable with that of the fundamental component) their effect on the pilot will be small relative to that of the fundamental.

Induced Currents in Isolated Bodies

Still another effect is possible even in cases where there is no connection either direct or through the capacitance of glove or shoe between the pilot and the conductors which carry the lightning current. This is the result of a transformer action in which the rapid changes in the magnetic field produced by the surge current induce currents in any neighboring closed electric circuit, such for instance as that of the pilot's heart. If the closed circuit is at an average distance l centimeter from a long straight conductor carrying the surge current I and if the maximum area of the circuit when projected on a plane which contains the conductor is a square centimeters, the instantaneous induced voltage is given by

$$E = 0.2 \frac{a}{l} \frac{dI}{dt} \times 10^{-8} \tag{11}$$

Taking $\frac{dI}{dt}$ as 100 kiloamperes per microsecond (that is, 10^{11} amperes per sec); l as 100 centimeters and a as 40 square centimeters (that is, roughly the area of the human heart) E comes out at 80 volts! This value exceeds, by a factor of many thousand, the potential difference produced normally in the heart muscle and picked up by the electrocardiograph. Of course, the duration of this voltage is short, say, 1 microsecond. If the circuit around the heart had a cross section of 1 square centimeter, a perimeter of 20 centimeters and a resistivity of 80 ohm-centimeters (a value sometimes quoted for body tissue), its resistance would be 1600 ohms. The crest value of induced current would be 50 milliamperes and the quantity of electricity circulated in a microsecond would be 0.05 microcoulomb. This estimated value is decidedly less than those computed as liable to be conducted through the limbs and body, but since it is induced immediately in a vulnerable organ the possibility of a very serious hazard is evident.

Physiological Effects

To judge whether or not the values of voltage, current, and charge estimated in the preceding sections are such as to constitute a serious hazard, information is needed as to the effects on the human system of electric shocks of very short duration. The problem is a very complex one because the effects depend upon many variables among which are the manner in which the current varies with time, the path of the current through the body, the timing of the surge relative to the normal heart cycle and individual differences in response.

As the intensity of the electric stimulus is progressively increased from a very low value, the first response is a sensation of "shock" or pain followed at about the same intensity by a "twitch" or involuntary contraction of one or more muscles. The stimulus required for such a minimal response is often called the "threshold" value and has been studied in human subjects under a variety of conditions. In much of this work the stimulus was a sustained alternating current. In figure 2 are plotted, to logarithmic scales, the root mean square values of threshold current, as a function of the frequency. Curve I by Kennelly and Alexanderson (reference 9) shows the average value for 5 observers of the root mean square current which could be tolerated "without marked discomfort or distress" from one hand to the other. Curve II by Carter and Coulter (reference 10) shows the average threshold values for 107 observers for current flowing between electrodes 1 square centimeter in area, in contact with the finger and thumb of one hand. Curve III shows values by the same authors on 15 observers using electrodes 25 square centimeters in area on the medial and lateral aspects of the distal part of the upper arm.

As the stimulus is increased, the sensation and the muscular contraction become greater. A higher level of intensity can be set by observing the value of a sustained alternating current at which the subject is just barely able to release the metal rod electrode which he had been grasping. This has been called by Dalziel (reference 11) the "let-go current," and data on it are shown in curve IV of figure 2. At this current the sensations experienced are exceedingly uncomfortable.

At still higher currents not only are the sensations still more painful but more serious effects appear. One of these is the onset of ventricular fibrillation, an uncoordinated succession of contractions of the muscle fibers of the ventricle which causes the pumping action of the heart to become ineffective and which causes death in a few minutes. Extensive experiments on this phenomenon by Ferris, King, Spence, and Williams (reference 12) have shown that if the electric current flows for a time which is short compared to the heart cycle, fibrillation will be initiated only if the shock occurs during that particular fraction of the heart cycle, designated as the "T wave," during which the contraction of the ventricle is relaxing. This sensitive interval occupies about one-fifth of the complete heart period. It has been found that after the current stops the hearts of smaller animals, rats, and guinea pigs, return automatically to their normal coordinated beating after a few seconds of fibrillation. In the case of larger animals, dogs, sheep, and man, the fibrillation persists until death ensues.

Larger currents tend to cause an inhibition of the respiratory centers which may persist for some time after the current stops, and may cause death from asphyxia unless artificial respiration is applied. With still larger currents hemorrhages may be caused in the spinal cord and brain and sometimes breaks develop in the larger arteries. Also, burns may be caused where the electrodes make contact with the skin.

Detailed studies of the mechanism of nerve action (reference 13) make it highly probable that a nerve impulse is triggered off when the ionic concentration at some point of the neuron wall is shifted by a critical amount. For an electric stimulus this implies that the flow of a certain current for a certain time (that is, the passage of a definite quantity of electricity) is required to produce a stimulus. After the nerve impulse has once started, it is self-propagating and leaves the neuron in a "refractory phase" during which it cannot be stimulated again for several milliseconds.

For very weak currents the diffusion of the ions appreciably reduces the net rate of accumulation of ionic concentration. The time required to reach the critical value is increased more than in proportion to the reduction in current value. Hence the total electric charge required for a threshold stimulus is greater. This may account for the turning upward of the curves of figure 2 at the low frequency end. For short applications, on the other hand, the effect of diffusion will be negligible and hence a constant threshold charge and a linear increase of threshold current with decrease in time of flow are to be expected. As a test of this relation figure 3 has been plotted, to logarithmic scales, with the duration of the surge current (or the duration of one-half cycle in the case of a-c. trials), as abscissa and with the quantity of electricity passing in the first swing of the surge (or in one-half cycle of the a-c. wave) as ordinate. Curves I to IV are derived from the correspondingly numbered curves of figure 2. Curve V shows the values of threshold quantity obtained by Conrad, Haggard, and Teare (reference 14) on five observers in experiments in which single current surges of rectangular wave form were passed between the first and second fingers of one hand while they were immersed in a saline solution to within about 1.5 centimeters of their junction. These curves indicate that a nearly constant value of charge is required to stimulate the threshold response if the duration of the surge is less than 100 microseconds.

The previously available data, summarized in the foregoing paragraphs, fall short of giving the information needed for interpreting the lightning hazard measurements in several respects. In particular,

(a) The surge data do not extend to time intervals as short as are encountered in lightning;

(b) The surges of curve V (fig. 3) were unidirectional (that is, a net charge of electricity passed through the tissues under test) as shown in insert (d), and the more common wave form of current induced by lighting (except for a direct stroke) will be one in which the first swing is followed by another in the opposite direction which will make the total electric charge passing in the circuit zero, as shown at insert (c) of figure 3;

(c) There was no indication whether the large margin which exists for long-duration shocks between threshold and danger also existed at shorter durations when the momentary current values were correspondingly high. The deaths of about 400 persons annually from lightning in the United States is, however, clear evidence that grave physiological effects can result from surges of short duration. Consequently, in the present study, a number of physiological experiments have been made, on a rather tentative and exploratory basis, to bridge over some of the worst gaps in the previously existing knowledge.

In the first series of tests, surges in which the current varied as indicated at insert (b) or as at insert (c) in figure 3 were passed between two cuff electrodes which surrounded the forearm of the human subject. The amplitude of the surge was adjusted until the subject was barely able to detect the occurrence of the surge. The results are plotted in curve VI of figure 3. It appears that over a considerable range in duration the threshold response was obtained when the part of the surge up to the first zero carried a charge of about 1 microcoulomb. It is interesting to note that at the shortest surge used the crest value of the threshold current was 4.5 amperes (that is, 45 times the value which, if maintained for a few seconds, is generally regarded as fatal). These results also show that there seems to be little difference in the threshold charge for surges of types (b) and (c).

The next tests were made with guinea pigs, using foil electrodes wrapped around two legs. Point A in figure 3 shows the average threshold of four guinea pigs for surges of the type shown at insert c, passing from one foreleg to the other. The threshold was located by noting the minimum surge at which a barely noticeable twitch of the legs was produced. The point marked B show the average threshold of three guinea pigs after the animals had been anesthetized by the injection of a barbiturate compound. More intense surges were then used and after each surge a cathode-ray oscilloscope with a suitable pre-amplifier was connected to the electrodes and the character of the cardiogram noted.

Because of the fact that it was not readily feasible to synchronize the timing of the electric surge with the heart cycle of the animal, the probability that any one surge should occur during the particular phase in which fibrillation can be initiated is about 1 in 5. In view of this, 10 trials were made at each value of surge intensity. The probability is only 1 in 9 that out of 10 shocks of random timing not one would occur during the sensitive phase.

Although the animals showed very violent spasmodic muscular contractions at the moment of shock, only minor changes in the character of the heart cycle and in the pulse rate were noted until the surges were very intense. One guinea pig withstood successively 10 shocks, of the type shown at insert (b) at each value of intensity and duration indicated by points C_1 to C_5, inclusive, and 2 shocks at C_6, after which the test was discontinued. The electrodes were attached to the two forelegs. After recovering from the anesthesia the animal appeared entirely normal.

A second guinea pig was similarly tested with surges of shorter duration and greater current and withstood 10 shocks of the type shown at insert (c) at each of the points D_1 to D_8, inclusive. No noticeable effect on the heart cycle was noted. The electrodes were then changed so that the charge passed between the left rear leg and the right front leg. It was then subjected to 23 shocks of the characteristics shown by D_8. Following the 2d, the 20th, and the 22d shock the cardiogram was abnormal for several seconds, suggesting that possibly a temporary fibrillation had been stimulated. The intensity was reduced and similar symptoms appeared after the 1st shock at D_6 and the 2d shock at D_7. At D_8 no fibrillation occurred, but the ST portion of the cardiogram was abnormal. During 20 more shocks at D_7 no fibrillation developed, but the pulse rate slowed down and the animal died shortly afterward. On autopsy it was found that the chest cavity was full of blood and the heart was free in the cavity. This suggests that the contractions produced by some of the later shocks had actually torn the larger blood vessels.

A third guinea pig was subjected to a total of 41 shocks in the range between points D_8 and D_5 of figure 3. The charge passed between right foreleg and left hind leg. After 9 shocks visible changes in the cardiogram were noted but not true fibrillation. The animal died after the 41st shock and an autopsy showed considerable damage to the heart tissue.

In view of the tendency for guinea pigs to recover automatically from fibrillation, further trials were made with dogs. One dog, under deep anesthesia from nembutal, was fitted with electrodes on left foreleg and right hind leg and subjected to surges of the type shown at insert (c), figure 3. Ten shocks were given at each of 5 intensities varying from point D_4 to D_8 (fig. 3). Only slight changes appeared in the cardiogram and after recovering from the anesthesia the animal appeared entirely normal.

A second dog was similarly connected and subjected to surges of the type shown in insert (b), figure 3. Ten shocks at each of the intensities shown at E_1 and E_2 caused no visible effect, other than the usual momentary strong muscular contractions. However, the first shock at E_3 started a definite fibrillation. An additional "counter shock" at E_4 caused no recovery and the fibrillating heart action continued with decreasing amplitude for about 15 minutes, when the animal died. An autopsy showed no significant damage to heart or lung tissue and it seems certain that death was caused by the fibrillation. The difference between this result and the preceding suggests that there may be a significant difference in the action of surges of the two types (b) and (c) in their tendency to produce fibrillation, although they are about equal as regards threshold intensity. Of course, these data are insufficient in volume to warrant any definite conclusion.

Another set of experiments was performed to see what effects might arise by transformer action when an anesthetized animal was placed in the neighborhood of a conductor which carried a rapidly varying surge current. The current wave was a slightly damped oscillation having a frequency of 40 kilocycles per second and an initial crest value of 200,000 amperes. Hence the rate of change of current had a crest value of 5.7×10^{10} amperes per second. The crest voltage which would be induced in a circuit 1 square centimeter in area and 10 centimeters away from the conductor would be about 10 volts. Numerous trials were made with anesthetized guinea pigs placed at various distances from the central conductor and in various orientations with respect to the magnetic field. In all cases when the animals were closer than 90 centimeters noticeable muscular contractions were produced at the moment of passage of the surge current.

A similar trial was made later on an anesthetized dog. For each of three positions, in which the magnetic field in the neighborhood of the animal's heart was directed successively in three nearly mutually perpendicular directions, 15 shocks were applied. The radial distance from the conductor to the heart was about 15 centimeters. Immediately after each shock the oscilloscope was connected to electrodes attached to the right front and left hind legs and the cardiogram was examined. In no case was any appreciable change in the heart action noted, although at each shock the animal's legs gave a decided jerk as a result of the induced electrical impulse. Ten further shocks of about half the current then were tried with similar results. After recovering from the anesthesia the dog appeared entirely normal. With this arrangement the induced currents in any organ would be similar to the type of surge shown in insert c of figure 3 in that the total net passage of electric charge would be zero. They would differ in that many more reversals of polarity would occur. The failure of this type of shock to cause fibrillation although it does cause marked muscular contractions may perhaps be related to this equality of the positive and the negative portions of the surge.

To the data already shown in figure 3 there may be added point F which indicates the charge and duration of the unidirectional surges used by Kouwenhoven and Langworthy (reference 15) in experiments on rats. When this discharge passed from head to tail, the rats were killed and hemorrhages were found in the spinal cord and brain. When this discharge passed transversely through the bodies to the ground plate on which the animals lay, the animals survived, provided artificial respiration was used on those which had a temporary respiratory inhibition.

Point G of figure 3 corresponds to 0.1 ampere, the 60-cycle value of current which Ferris et al (reference 12) estimate is the minimum at which fibrillation of the human heart is to be expected; and point H corresponds to the generally recognized 60-cycle threshold of sensation of 1 milliampere.

In considering figure 3 it should be kept in mind that the theoretical basis for expecting the alternating-current threshold values, such as curves II and III, to be uniquely related to the charge per half cycle which is plotted as ordinate is rather tenuous. The physical damage produced by shocks such as those indicated by D_G which killed guinea pigs by damaging tissue is probably not proportional to the charge in an individual shock but increases with repetitions of the shock and may vary with the energy dissipated or with the square of the charge. Nevertheless, in the absence of any better form of presentation figure 3 may be used as a basis for arbitrarily selecting a safe operating limit. It appears that if the charge passing through the body can be kept down to a value of 1 microcoulomb the personnel would not experience any noticeable shock at the time of a lightning stroke. Such a limit, however, would presumably require the installation of a rather extensive system of lightning conductors. It is perhaps wiser to choose a higher limit, say 10 microcoulombs. The shock produced by such a surge will be very noticeable and may lead the personnel to question an assertion that the aircraft is protected at all. However, figure 3 indicates that such a shock, while decidedly unpleasant, is less intense by a factor of 40 than that which was barely enough to cause fibrillation in a small dog. It will, therefore, be taken as the upper safe limit in the following discussion.

Safety Limits

To combine the various estimates made in the foregoing sections, the value of 60,000 amperes for A, the crest current in natural lightning, the permissible charge of 10 microcoulombs for Q_s and the effective resistance of 300 ohms for R_1 may be substituted in equation (6). This yields M = 0.05 microhenry as the allowable coupling between the lightning circuit and the personnel. In the laboratory tests which will be described the crest rate of change of current was about 13 kiloamperes per microsecond and the crest voltage induced by a coupling of 0.05 microhenry would be 650 volts. In these experiments, therefore, readings of less than 500 volts may be considered as safe. Values exceeding this figure are indicated by asterisks in the tables.

In estimating the values of voltage for which insulation might be provided, the values of voltage observed in the laboratory tests should be multiplied by about ten because the crest rate of change of current in natural lightning may exceed that used in the present tests by this factor.

In estimating the hazard from currents induced electromagnetically in a person who is entirely insulated from the lightning current path, it may be assumed that the distance from the path to the person's heart is at least 100 centimeters, that is, six times that used in the animal tests. The probable rate of change of current may be three times that used in the tests on animals so that the rate of change of magnetic field would be only half of that which failed to affect the dog. In the absence of much more complete data it is, of course, impossible to estimate the margin of safety, if any, which exists with respect to this hazard. The possibility of danger from this source certainly constitutes a further reason for the use of a plurality of lightning conductors which can share the current and thus greatly reduce the magnetic field inside the aircraft.

Still another consideration arises from the fact that many lightning strokes contain, in addition to the sudden high current surges, a continuing discharge at a few hundred amperes which may last for several tenths of a second. The division of this current between the pilot and the metallic circuits which may shunt him will depend on the resistance rather than the inductance of the latter. If the limiting safe current is taken as 0.025 ampere, while the lightning component is 2500 amperes, that is, 10^5 times as great, and if the pilot's skin can raise his effective direct-current resistance to 2000 ohms the resistance of the shunt path should be less than 0.02 ohm. This should be attainable by careful bonding but does not leave much margin for careless workmanship.

METHODS OF TEST

Discharge Circuit

The transient currents for the tests were obtained by the discharge of a surge-current generator. This consisted of 40 capacitor units, each of 1μf capacitance. They were connected in series in pairs and the 20 pairs were in parallel. The resulting capacitance of 10 μf could be charged to 100,000 volts by a 12 kva transformer with kenotron rectifiers. The circuits are shown in figure 4.

The discharge circuit included a 2-ohm damping resistor, a 3-ball spark gap, by which the discharge could be triggered and synchronized with the oscillograph, and the test circuit through the aircraft. The ground side of the surge current generator was connected by a network of short copper bars to the steel grid imbedded in the floor of the laboratory. One terminal of the test circuit (the nose of glider XCG-7, fig. 5, or the tail of the PT-19A airplane) was also connected to this imbedded steel mesh. The resistance was chosen so as to make the discharge nearly critically damped, as is shown by the typical oscillogram of current (fig. 6) taken with a resistive shunt connected in the discharge circuit.

The small ripple at the beginning of this current wave is apparently the result of oscillations which involve the capacitance of the airplane to ground. Although this oscillation is of very small magnitude (only 0.4 percent) relative to the fundamental component of the current, its frequency is high (approx. 6 megacycles per sec) and the rate of change of current caused by it is correspondingly great. If an inductive shunt (M = 0.0986 microhenry) is connected in series in the circuit the electromotive force across it has the form shown in figure 7 and gives a direct indication of the instantaneous values of di/dt. Figure 8 taken with a faster sweep shows the initial part of this wave in greater detail. At least two high-frequency components are evident. Skin effect in the resistive shunt and the self-inductance of the secondary of the inductive shunt attenuate the higher frequencies to half their actual value at about 10 and 25 megacycles per second, respectively. It is, therefore, possible that the current contained still other components of a frequency higher than these limits. Such components might result from electrical oscillations of wavelength comparable with portions of the aircraft, shock-excited by the main discharge.

The crest value of surge current is approximately inversely proportional to the inductance of the circuit. The arrangement of the leads to the aircraft was, therefore, a compromise between the conflicting requirements of low inductance and a large clearance between the aircraft and the return leads. A typical circuit for the PT-19A airplane is shown in figure 9. Here the inductance of the discharge circuit was 9 microhenries and the crest current 38,000 amperes.

MEASUREMENT OF INDUCED VOLTAGE

In most cases the crest value of the induced voltage was indicated by an entirely self-contained electronic crest voltmeter. This instrument consisted of an adjustable capacitance potential divider which supplied an electronic trigger circuit. The grid bias of the trigger tube could be adjusted in succession to a number of different values until one was found at which the circuit was barely triggered when the surge occurred. Calibration of the voltmeter at radio frequency gave the relation between the bias for triggering and the applied voltage. To minimize the time and the number of surges required, no attempt was made to locate the crest value closer than about 15 percent. By adjustment of the capacitance divider five ranges could be obtained: 0-270, 0-540, 0-1350, 0-2700, and 0-5400 volts.

In those cases in which one extremity of the airdraft could be maintained nearly at ground potential by providing connections of very low inductance between it and ground, it was found practicable to use the high-speed cathode-ray oscillograph for the voltage measurement. For this purpose the cable from the oscillograph was led along the ground connection and into the cockpit where its sheath was connected to the pilot's seat. The central conductor was connected to some other point at which the voltage was to be measured. Figure 10 shows a typical voltage oscillogram obtained in this way. The wave form of this induced voltage is very nearly the same as that for the time rate of change of the total current as shown in figure 7. The sensitivity of the oscillograph was about 280 volts per centimeter, and the surge impedance of the cable was 50 ohms.

A major difficulty in making the voltage measurement arises because of the leads which are needed to connect the voltmeter, or the oscillograph cable, to the points at which measurements were desired. In most cases the shielding container (a can approx. 17 cm in diam. and 20 cm long) of the voltmeter, or the grounded sheath of the cable was tied to the pilot's seat and a wire was run from the line terminal of the voltmeter on the core of the cable to each of the other points, wheel, pedal, throttle, flap control, and so forth, in succession.

The first uncertainty arises from the fact that the electric field around a conductor carrying a changing current is not lamellar and hence the observed voltage between two points depends, in general, on the location of the voltmeter lead as well as upon the location of the two points. This ambiguity was minimized by placing the lead in about the same location as that which the pilot's arm or leg would normally occupy.

Greater uncertainty is caused by the self-inductance of the lead which was of the order of 1 microhenry. Any current flowing in this lead will cause the measured voltage to be different from that between the points to which the lead is connected.

When the cathode-ray oscillograph is used for these voltage measurements its connecting cable has a surge impedance of only 50 ohms. Hence the current in the leads is fairly large. The inductive reactance of the lead would be equal to this surge impedance for an oscillating component which had a frequency given by $f = R/2\pi L$ (in this case about 10^7 cycles per sec). Hence components of matererially higher frequencies will be unduly attenuated.

On the other hand, where the electronic crest voltmeter is used, its capacitance of about 12 micromicrofarads will be in series resonance with the inductance of the lead at a frequency of about 5×10^7 cycles per second. Components of frequency near this value will (unless heavily damped) be magnified and produce an excessively high response. To limit this resonance, a resistance of 50 ohms usually was kept connected across the terminals of the electronic voltmeter. With this arrangement the simple voltmeter circuit should be reasonably accurate up to about 6 x 10^6 cycles per second.

Still another cause of current in the measuring lead is capacitance between the lead itself (particularly the end next to the voltmeter) and other parts of the main circuit or ground. The voltage across such a capacitance may be relatively large and the effect of the resulting current relatively considerable. The use of the 50-ohm resistor across the voltmeter helps to reduce spurious effects of this sort.

Another uncertainty is introduced by the superimposed oscillations of high frequency. As these are the result of the capacitance between parts of the aircraft and the floor, it is possible that their magnitude at the shunt may be quite different from that at points within the aircraft itself. However, the use of the 50-ohm resistor in parallel with the crest voltmeter made this instrument relatively immune to their effects.

RESULTS

Measurements on the Main Fuselage Section of Glider XCG-7

The XCG-7 glider was used as an example of nonmetallic aircraft. The structural parts of this glider consist almost entirely of wood, the only metal parts being control cables and tubes; radio, telephone, and light wires; fittings for control surfaces; and so forth. These conductors form a good path for a lightning stroke to the glider, but if they are insulated from each other, as was the case for the XCG-7 glider as received, the path of the lightning stroke may include several of these conductors in series and in getting from one conductor to the next it may pass, in full strength, through the body of one of the occupants of the aircraft. This is obviously a severe hazard which can and should be eliminated by bonding all metal parts of the glider together with short and direct ties equivalent to No. 13 copper wire or larger. Even with all metal parts bonded there still remains the question whether or not a dangerously high voltage will be induced between two points on the resulting conductor system across which an occupant of the glider may be bridging. The problem then is to measure these induced voltages for a simulated lightning discharge as described previously and to determine whether or not they are a source of hazard to the glider personnel. This was done for the following conditions of bonding and also after the addition of external lightning conductors:

(a) Minimum bonding required to make a complete metallic path for the discharge,

(b) Bonding as recommended to keep the induced voltages low,

(c) Bonding plus additional lightning conductors outside the glider,

(d) Separate lightning conductor system outside the glider.

Apparatus and connections.- The main fuselage section of glider XCG-7 was placed near the surge-current generator as shown in figure 5, and supported on cribbing of paraffin-impregnated lumber. This section of the glider was chosen for the experimental work because all personnel and cargo are housed within it during flight and most of the metal parts of the entire glider are in this section. The control cables for the tail surfaces come to the rear end of this main section in a closely set group, and the addition of the rear fuselage section merely extends these cables in a straight line. All control cables and tubes for the wings are complete in this main fuselage section up to the points where the wings are attached. A lightning discharge entering the glider from a wing or the tail would come in on these control cables or on lightning conductors if they were added, and the extra length of conductor obtained by actually having the wings and tail section in place would not materially affect the path of the discharge within the main fuselage section. Moreover, a wing-to-nose discharge would be substantially the same as a tail-to-nose stroke at the pilots' seats which are well forward of the wings, provided a complete bond of all conductors were made where the wings are attached to the main fuselage section. Therefore, the experimental data were obtained by passing the discharge from the surge-current generator in at the rear of this main fuselage section and out at the nose.

The high voltage positive terminal of the surge-current generator was connected through the 2-ohm damping resistor, to a 2-inch copper strap (used as a terminal for attaching the glider conductors) at the rear of the glider section by two No. 8 copper wires in parallel spaced 12 inches apart. The copper strap is shown spanning the top of the circular end frame in figure 5. The tow-cable fitting in the nose of the glider was connected to the imbedded steel in the floor of the laboratory by two No. 8 copper wires in parallel. Either a resistive shunt or an inductive shunt was connected in series with this lead and located at the connection to the steel in the floor for measuring current and rate of change of current, respectively. When the surge-current generator was discharged through this circuit the current as measured on a cathode-ray oscillograph connected to the resistive shunt by a 50-ohm cable was found to be a critically damped sine wave with a maximum current of 35,000 amperes as shown in figure 6. The maximum rate of change of current through the glider as determined by measuring the first peak of the superposed oscillation on the oscillogram of figure 8 was 13 kiloamperes per microsecond. For the fundamental component only, the maximum rate of charge of current was 6.6 kiloamperes per microsecond. When lightning conductors were added on the outside of the glider fuselage and connected in parallel with the system of conductors formed by the control cables inside the glider or when the outside conductors were used alone, the values of current and rate of change of current did not differ from the foregoing values by as much as 10 percent.

Check of calibration of crest voltmeter. - Nearly all of the measurements of induced voltage in the glider were made with the electronic crest voltmeter (described previously). In order to check the calibration of this voltmeter and to get a complete record of the wave form of the induced voltage, a measuring cable from the cathode-ray oscillograph was inserted into the glider through the tow-cable tube at the nose of the glider, with the sheath of the cable connected to the pilot's seat and the center conductor to the other points on the glider conductor system within reach of the pilot. Figure 10 shows a typical oscillogram of the induced voltage thus obtained from the front seat to the "cable release knob." The insertion of the measuring cable in the glider added another conductor to the already complicated network and probably changed the values of induced voltage as measured inside the glider; therefore, the data obtained with the measuring cable and cathode-ray oscillograph were not used as a direct measure of the induced voltage, but merely to get a general idea of its wave form and as a check on the electronic crest voltmeter. Since the measuring cable had a surge impedance of 50 ohms, in order to duplicate this with the voltmeter a 50-ohm noninductive resistance was installed across its terminals. With the measuring cable in place and its sheath connected to the front seat, oscillograph measurements were taken with the central conductor of the cable connected to five different points within reach of the pilot. With the central conductor of the cable disconnected, measurements with the crest voltmeter were made to these same five points. The crest voltage as obtained from the voltmeter agreed quite closely in every case with the first peak of the superposed high frequency oscillation on the corresponding oscillogram. The oscillograms also indicate that the maximum of the fundamental component is in each case about two-thirds of the first peak of the superposed high frequency. Thus the electronic crest voltmeter with the 50-ohm resistor across its terminals can be used as a fairly accurate measure of the maximum of the fundamental component of induced voltage if its peak reading is multiplied by two-thirds. The measuring cable was then removed from the glider, and measurements of the induced voltages were made using the electronic crest voltmeter with the 50-ohm resistor across its terminals.

Measurements with minimum bonding. - As noted in the first paragraph of this section, control cables run almost the entire length of the glider fuselage, but they are insulated from each other and from other metal parts of the glider. To obtain a complete metallic path for the discharge through the glider, some bonding of the metal parts inside the glider was needed. The 8 control cables extending to the rear of the glider were all bolted to the 2-inch busbar at the rear of the main fuselage section, this busbar serving as the high-voltage terminal for the main discharge. Just to the rear of the cargo compartment all control cables (those to wings and tail) were bonded together, thus providing a common point in the conductor system where the wings are attached to the main fuselage section. All these control cables, 14 in all, run from this point through raceways in the bottom of the glider to the nose where the pilot's seat is located. Six of them enter the space in the floor between the 2 metal seats in the nose of the glider (for pilot and co-pilot) and are connected to the metal control sticks and pedals. The rear seat is electrically connected to these 6 cables through metal fittings, but the front seat is insulated. To complete the bonding, two No. 12 copper wires were run from the rear seat to the front seat and to the tow cable fitting which extends through the nose of the glider and which was used as the ground terminal for the main discharge. The other 8 control cables run to controls located beside the pilot's seat and they were not connected to the bonded system of conductors at this point.

The surge-current generator was discharged through this bonded system of conductors inside the glider, and measurements of induced voltage from the pilot's seat to several controls within reach of the pilot were made using the crest voltmeter. The results of some of these measurements are given in the first column of table I. These voltages are all quite high, especially the one to the flap control which was connected to control cables running to the common bond just to the rear of the cargo compartment but which was not connected to the bonded system at the pilot's seat.

To simplify the interpretation of these experiments, their results are arranged in table II. For instance, in the first column and the first row the value of 1300 volts gives the voltage measured between the front seat and the right pedal. Multiplying this by the factor 2/3 gives the value 868 in the second row which shows the fundamental component of the induced voltage. Dividing this by the rate of change of the fundamental component of current, 6.6×10^9 amperes per second, gives 0.13 microhenry for the coupling inductance between the stroke path and the pilot's leg. Multiplying this value by the probable extreme rate of change of current in a lightning stroke; namely 144×10^9 amperes per second gives 19,000 volts as the induced voltage in the branch circuit tending to puncture the pilot's shoe. If the shoe is conducting, or punctures, the charge then passing through his leg would be given by equation (6) as $60,000 \times 0.13 \times 10^{-6}/300 = 26$ microcoulombs (listed in the 5th row), which would give a very disconcerting contraction of the pilot's muscles.

<u>Measurements with recommended bonding</u>. - The results obtained with minimum bonding indicate that additional bonding is advisable wherever it can be conveniently installed. The pulleys for the control cables on this glider are made of insulating material but are mounted in metal fittings. In

order to get as many electrical ties as possible between these cables, it would, in the future, be advisable to use instead some kind of metal pulleys. On the assumption that this could be done, the control cables were bonded to the pulley fittings at each pulley and wherever pulley fittings are close together, but insulated, they, too, were bonded. The eight control cables not already connected to the bonded system at the nose of the glider were bonded at this point by short lengths of No. 12 copper wire. All other metal parts of the glider which have an appreciable length - such as light wires, radio and telephone wires, and metal tubing for airspeed, bank, and rate-of-climb instruments - were each bonded to the control-cable system of conductors in at least two places.

Measurements of induced voltage were made with this complete bonding system, and the results are given in the second column of table I. The second column of table II shows computed values based on one of these measurements.

Measurements with recommended bonding plus additional lightning conductors outside the glider. - Measurements of induced voltage between the same four points used previously were made after additional lightning conductors had been attached to the outside of the glider and connected in parallel with the inside system of conductors. These additional conductors were located as follows: (1) one 6-inch-wide strip of thin copper ribbon over the top of the glider (2) one No. 12 copper wire over the top of the glider (3) three No. 12 copper wires, one over the top and one at the bottom of each door (4) six No. 12 copper wires, one over the top, one along the keel, one at the bottom of each door, and one under each wing. The results of these tests are shown in columns 3 to 6 of table I.

It may be noted that: (1) the No. 12 wire and 6 inch strip are almost equally effective in reducing the induced voltage and (2) the addition of lightning conductors considerably reduces the induced voltage between some points, but it does not materially affect that between others. In such a complex network as that formed by the conductors inside the glider it may be said correctly that "almost anything can happen - and it usually does." However, a somewhat more helpful explanation may be obtained by considering that there are, in general, two different types of pairs of points between which induced voltage may be measured. The conductor system inside the glider consists, in effect, of a number of inductors in parallel, with cross ties between them at some places. The two types of pairs of points are then (1) two points on the same inductor and (2) one point on one inductor and the other point on some other inductor. The induced voltage for a type (1) pair of points would be expected to decrease as additional lightning conductors are added because this voltage is proportional, mainly, to the current in one inductor only and as circuits are added in parallel the current in any one inductor should decrease. The cable release knob and "right pedal" are two examples of type (1) pairs of points in table I. For type (2) pairs the induced voltage results from an unbalance of the impedance drops in two different inductors and the addition of a lightning conductor by reason of mutual inductance, may decrease the current in one of these circuits by a different percentage than that in the other. This will alter the "balance" between the two points allowing the induced voltage to increase slightly in some cases. The "flap control crank" and "spoiler control handle" are two examples of type (2) pairs of points in table I.

A complete survey of the induced voltages between pairs of points across which an occupant of the glider might be bridging was next made using the crest voltmeter. The six No. 12 copper-wire external lightning conductors were used in parallel with the inside system of conductors for these tests. Although they may not be necessary for protection from induced voltage such conductors would probably be essential to insure that a direct stroke will be intercepted by a conductor before reaching the bodies of any of the occupants. The results of measurements between each of the pilots' seats and other metal parts within reach of the pilots are shown in table III. These induced voltages are all within the probable safe limit except the one from "front seat" to "radio switch." During this measurement, (a) the radio set was bonded to the inside conductor system by No. 12 copper wire about 5 feet long running directly to the system of control cables beneath and between the two seats, (b) the lighting wires were connected directly to the radio set and ran to the rear of the glider where they were bonded to the control cable system just behind the cargo compartment and (c) a short tie from the pitot tubes ran to the nose of the glider where it was bonded to the tow cable fitting.

When the lighting wires were disconnected from the radio set and tied directly to the system of control cables between the seats the induced voltage between the front seat and radio switch was reduced from the original 750 volts to 300 volts. The reduction suggests that any wire or cable which is bonded to the main system of conductors at the rear of the glider and then run forward should be bonded to the main system of conductors at the forward point before going to any metal within reach of the personnel. When the 5 foot long No. 12 copper wire tie from the radio set to the system of conductors between the seats was removed, the induced voltage from the front seat to the radio switch increased to 1450 volts, indicating that a conductor bonded at one point in the glider and then running to a second point where it can be reached by the personnel, should also be tied to the conductor system at the second point even though the total length of the conductor is only a few feet.

Occupants of the glider other than pilot and co-pilot are seated so that none of them is likely to be in contact with two points on the conductor system at any one time. However, to determine the necessity for keeping the passengers insulated from the conductor system, voltage measurements were made between the various control cables in the raceways, which serve as seats for these passengers. The induced voltages measured between the left flap control cable and each of the five control cables in the right raceway at points in the plane of the glider doors were all found to be between zero and 400 volts. However, when one of the points of contact with a cable was moved aft by 30 inches the induced voltages were found to be about 500 volts. Thus, for some cables the change was as much as 200 volts per foot. If these cables were exposed so that an occupant might come in contact with two points on the cable system at the same time and considering the maximum axial distance between these two points to be 6 feet, the voltage might be as much as 1200 volts. It, therefore, would seem advisable to keep the cables insulated from the personnel wherever possible.

<u>Measurements with lightning conductor system insulated from inside conductors.</u> - All the foregoing discussion of induced voltage is based on the assumption that all metal parts of the aircraft, both the bonded system of conductors inside the glider and any protective system of conductors added on the outside are to be connected together forming one conductor system. This was thought to be the most readily applicable method of protection.

Another method of protection would be to have the inside bonded system of conductors entirely insulated from the outside system of lightning protective conductors. This would require (1) all metal parts of the glider which might intercept a stroke of lightning, such as metal fittings on tail and wing control surfaces, to be connected to the protective conductor system and insulated from the inside conductor system and (2) the protective system of conductors to be properly insulated from all of the glider personnel. In order to accomplish this isolation of the two conductor systems: (1) all control cables going to the tail and wings would have to be equipped with strain insulators before entering the main fuselage section; (2) fittings and controls for landing gear and tow cable would have to be well insulated from the glider personnel and from the inside conductor system and; (3) special insulation would have to be installed on pitot tube, radio aerial, and so forth. If these insulation requirements can be attained, this would be an ideal method of protection because none of the lightning current would flow in the inside conductor system and the magnetically induced voltages as measured previously would be very much reduced.

The voltage for which insulation must be provided is the induced voltage in the inside system of conductors running from the nose of the glider to the tail or wing tip (this voltage may be divided by two if it is assumed that it divides equally between the two gaps across which it might cause breakdown). A measure of this voltage was obtained on glider XCG-7 by disconnecting the inside conductor system, control cables, and so forth from the copper strap at the rear of the main fuselage section, while the six added lightning conductors on No. 12 wire were still attached to it. The electronic crest voltmeter was then connected, through a 10:1 resistance potential divider, between the inside conductor system and the external lightning conductors at the rear of the glider. The peak voltage thus measured, when the 35,000 ampere discharge was sent through the six lightning conductors on the outside of the glider, was 15 kilovolts. Measurements with a single No. 12 copper wire in place of the inside system of conductors gave voltages from 9 to 13 kilovolts depending on the location of the wire inside the glider. These voltages were also measured by (1) a previously calibrated klydonograph with a resistance divider added and (2) the cathode-ray oscillograph with its measuring cable run inside the glider and a 500-ohm noninductive resistor in series with the center conductor. The klydonograph records gave voltages agreeing with those obtained by the crest voltmeter to within 25 percent. The oscillograph measurements were made with a single No. 12 copper wire tied to the lightning conductors at the rear of the glider and then brought approximately along the central axis of the glider to its nose where the wire was connected to the 500-ohm resistor in series with the center conductor of the measuring cable. The cable sheath was connected to the tow cable fitting at the nose of the glider. An oscillogram of this voltage is shown in figure 11. The peak voltage is 17 kilovolts and the maximum of the fundamental component 9 killovolts. The corresponding voltage as measured by the surge-crest voltmeter and the klydonograph was 10 kilovolts. An average of all the values obtained by these three methods give an induced voltage of 15 kilovolts for the entire length (22 ft) of the main fuselage section of glider XCG-7, that is, 680 volts per foot. To obtain the voltage that the insulation between the inside and outside conductor systems of a glider in flight should be designed to withstand, (1) multiply the above value of volts per foot by the total length of the glider; (2) multiply by 5, on the assumption that the maximum rate of change of current in an actual lightning discharge, (the median stroke in McEachron's data) is five times the value (13 kiloamperes per microsecond), for the 35,000 ampere discharge used in the voltage measurements; and (3) divide by 2, since the voltage must break down the insulation in two places. For a glider 50 feet long the voltage per gap on this basis turns out to be 85 kilovolts.

The problem of insulating the inside conductor system (including the personnel) of an aircraft from the outside lightning conductor system to withstand peak voltages of approximately 85 kilovolts should be considered for each design of aircraft to be protected. However, it is doubtful that the additional safety provided by such insulation would warrant the expense of its installation. The first method of protection considered, in which all the conductors on the aircraft are bonded to form one system, should give sufficient protection if the bonding is properly done.

Measurements on the PT-19A Airplane

A Fairchild dual-control training airplane type PT-19A was used as an example of combination metal and wood aircraft. The fuselage of this airplane is constructed of a welded steel tube frame covered with fabric and plywood. The wings consist of wood ribs with a plywood skin, the only metal parts being control tubes for pitot tube on one wing, light wires, and landing gear and fittings. All metal parts of this airplane are well bonded to form one conductor system and no extra bonding or added conductors were used for the induced voltage tests.

The airplane was completely assembled and placed on the floor of the laboratory near the surge-current generator as shown by the photograph in figure 9. The two front landing wheels were placed on 10-inch-high wood platforms to supplement the insulation of the rubber tires. The tail of the airplane was blocked up from the floor; the rear landing wheel removed, and two short copper strips were run from the rear landing wheel fitting to the laboratory floor, thus grounding the tail of the airplane to the ground side of the surge-current generator. The high voltage terminal of the generator was connected in series with the 2-ohm damping resistor to the right-hand flap control fitting (nearest the fuselage) by two No. 8 copper wires in parallel spaced 12 inches center to center. This gave a discharge path from right wing to tail of the airplane. For the nose-to-tail discharge, the high voltage lead was connected to the hub of the propeller. For the wing-to-wing discharge the high voltage lead was connected as in the right-wing-to-tail discharge, the ground connection was removed from the tail, and the left-hand flap control fitting (nearest the fuselage) was grounded to the floor of the laboratory by two No. 8 copper wires in parallel.

Records of current and rate of change of current when the surge-current generator discharged through each of the three paths previously described were obtained by using the cathode-ray oscillograph and a resistive shunt or an inductive shunt in the ground lead of the discharge path. Values obtained from these records for all three discharge paths agreed to within 10 percent and the following results are the averages for all records taken: (1) maximum current - 38.8 kiloamperes; (2) maximum di/dt (first peak of superposed oscillations) - 17 killoamperes per microsecond and; (3) maximum di/dt of the fundamental component - 9 kiloamperes per microsecond. Typical oscillograms are shown in figures 12, 13, and 14. These values are all slightly higher than the corresponding ones obtained with glider XCG-7 in the discharge circuit; therefore the limiting value of induced voltage (500 volts) deduced to be safe in the glider experiments will indicate somewhat greater safety in the PT-19A experiments to be described.

Values of induced voltage in each cockpit of the airplane were measured when the surge-current generator discharged through each of the three paths (1) wing to tail; (2) nose to tail; and (3) wing to wing. The electronic crest voltmeter with a 50-ohm resistor across its terminals was used for most of these measurements. For the wing-to-tail and nose-to-tail discharges, measurements were also made with the cathode-ray oscillograph, by placing the 50-ohm cable inside the fuselage from the tail of the airplane up to one of the seats. The addition of the measuring cable was found (as checked with the crest voltmeter) to have very little effect on the magnitude of the induced voltage being measured in these experiments. This is accounted for by there being such a muitiplicity of conductors in the fuselage from tail to seat that the addition of one more (the measuring cable) has little effect. The oscillogram in figure 14 is a record of the induced voltage between the rear seat and the control stick for a wing-to-tail discharge.

The schematic diagram of the PT-19A in figure 16 shows all of the control handles and knobs with which a pilot might come in contact and assigns a letter to each of them. Voltages were measured from the seat to each of these lettered points and the results are given in table IV. All values measured were below the safe value of 500 volts; therefore, it is concluded that the personnel in an aircraft, with a welded steel tube fuselage, would be well protected, even without additional lightning conductors, from electric shock due to induced voltages during a lightning discharge through the aircraft.

CONCLUSIONS

The results of the experiments previously described indicate some general principles to be followed for the protection of the personnel in a nonmetallic aircraft against the hazard of induced voltage when a lightning stroke discharges through the aircraft:

1. All metal parts of the aircraft should be bonded at as many points as feasible to form a single conductor system inside the aircraft. Cables, wires, and tubing more than 3 feet long should be bonded at both ends.

2. At places, such as the pilot's seats, where an occupant of the aircraft is likely to come in contact with two or more conducting parts on this conductor system,

special care must be taken in bonding the metal parts. At such places all control cables and other metal parts which extend over any appreciable length of the aircraft should be bonded directly to common points with leads having a minimum inductance, before connecting to any exposed metal parts.

3. All control cables, radio wires, and other conductors extending for an appreciable length of the aircraft should be kept fairly close together in one small part of the cross-sectional area of the fuselage, so that they can be easily insulated from the personnel. Between points at which they are all tied together, they should be insulated from the personnel.

4. The addition of extra lightning conductors outside the aircraft connected in parallel with the inside system of conductors, in general, decreases the magnitude of the induced voltages inside the aircraft.

5. The use of insulation on pedals, control stick, and so forth, might reduce the charge passing through the pilots' limbs by a factor of 10 or more, but it is very doubtful if such insulation could be relied upon under all conditions. Hence its use should not be regarded as a justification for omitting any bonding of conducting members.

6. The provision of a complete lightning conductor system insulated from the control cables and personnel seems to constitute an impractical ideal.

7. Currents induced in animal tissue by transformer action from rapidly varying currents can produce severe muscular contraction, though perhaps not ventricular fibrillation. Hence the provision of a plurality of lightning conductors electrically in parallel and on opposite sides of the personnel is desirable.

8. The personnel enclosed in an aircraft which has a fuselage of metal framework construction are reasonably well protected from induced voltage shock without other protection.

National Bureau of Standards,
Washington, D. C., Sept. 28, 1944.

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Table I - Induced voltages in glider XCG-7 as measured by the electronic crest voltmeter with a 50-ohm resistor across its terminals. 35-kiloampere discharge through glider (see figure 6). A positive polarity indicates that the potential of the seat was above ground by more than the potential of the other point.

Voltage measured from front seat to	No extra conductors Minimum Bonding	No extra conductors Recommended Bonding	One 6" wide Cu strip	One No. 12 Wire	Three No. 12 Wires	Six No. 12 Wires
Cable release knob	+ 2200*	+ 800*	+ 500	+ 500	+ 350	+ 200
Right pedal	+ 1300*	+ 650*	+ 400	+ 500	+ 350	+ 250
Flap control crank		- 450	- 500	- 500	- 500	- 350
Flap control	- 4000*	- 100	- 140	- 200	- 180	- 50

*Values considered hazardous to glider personnel

Table II - Computations based on the induced voltages between front seat and right pedal of glider XCG-7 as measured by the crest voltmeter with a 50-ohm resistor across its terminals.

	No extra conductors Minimum Bonding	No extra conductors Recommended Bonding	One 6" wide Cu strip	One No. 12 Wire	Three No. 12 Wires	Six No. 12 Wires
Peak voltage as measured	1300*	650*	400	500	350	250
Maximum of fund. comp. of induced voltage	868*	434*	267	333	233	167
Mutual inductance in microhenries	0.13*	0.066*	0.04	0.05	0.035	0.025
Maximum induced voltage (for an actual lightning stroke)	19,000*	9,500*	5,800	7,200	5,000	3,600
Maximum quantity through occupant in microcoulombs (for an actual lightning stroke)	26*	14*	9	10	7	5

*Values considered hazardous to glider personnel

Table III - Induced voltages in Glider XCG-7 as measured by the electronic crest voltmeter with 50 ohms across its terminals.
Six No. 12 copper wire external lightning conductors were added in parallel with the inside conductor system. 35000-ampere discharge through glider.

Voltmeter connected		Crest Volts
From	To	as measured
Front Seat	Elevator trimmer control	-250
" "	Rudder " "	-250
" "	Radio switch	-750*
" "	Talk knob	-400
" "	Left pedal	+250
" "	Nut on control wheel	<200
" "	Bottom of control stick	<200
Rear Seat	Nut on control wheel	<200
" "	Bottom of control stick	<200
" "	Right pedal	<200
" "	Left Pedal	<200

*Values considered hazardous to glider personnel

Table IV - Induced voltages in plane PT19A as measured by electronic crest voltmeter with 50 ohms across its terminals or from C R O oscillograms. 38000-ampere discharge through plane (see fig.12). A negative polarity indicates that the potential of the seat was above ground by more than the potential of the other point.

Voltage measured from seat to	Front Cockpit Discharge path			Rear Cockpit Discharge Path		
	Wing to Tail	Nose to Tail	Wing to Wing	Wing to Tail	Nose to Tail	Wing to Wing
Control stick - J	< 100	<100	<100	475	350	170
Trimmer control - T	- 300	- 300	200	-290	-260	200
Throttle - H	< 50	<100	<100	-	-	<160
Gas tank control - G	<50	<100	<100	150	-	<160
Flap control - F	-	<100	<100	220	-	<160
Wobble pump - W	-	<100	<100	150	-	<160
Ignition - I	-	<100	<100	180	-	<160
Left pedal - P	< 50	<100	<100	250	210	<160
Right pedal - P	<50	<100	<100	180	190	<160
Hand brake - B	-	<100	<100	-	-	-
Control lock - L	<50	-	-	170	-	<160
Carburetor - C	-		<100	-	-	<160

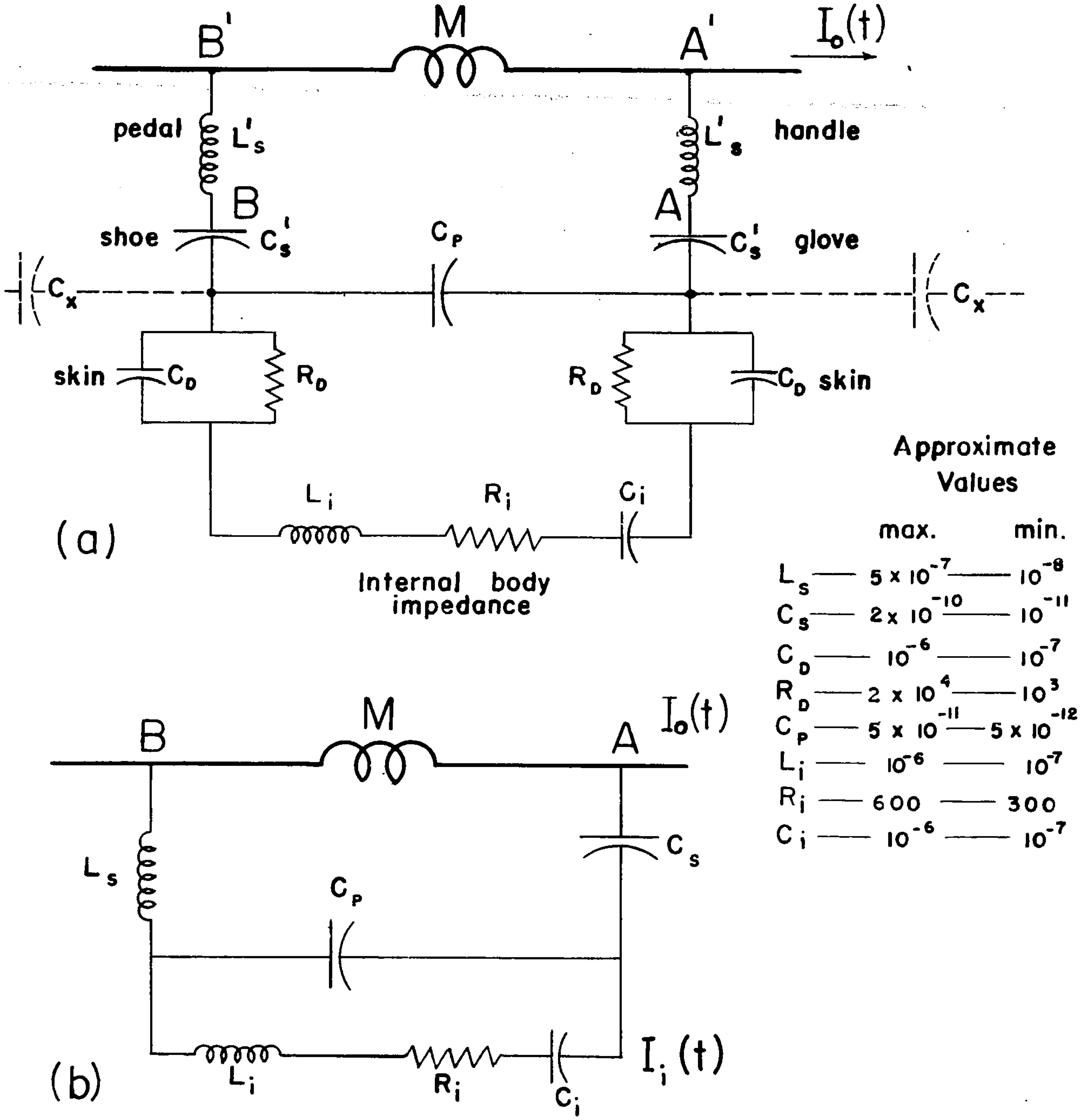

Figure 1.- Circuit equivalent to human body shunted by lightning conductor.

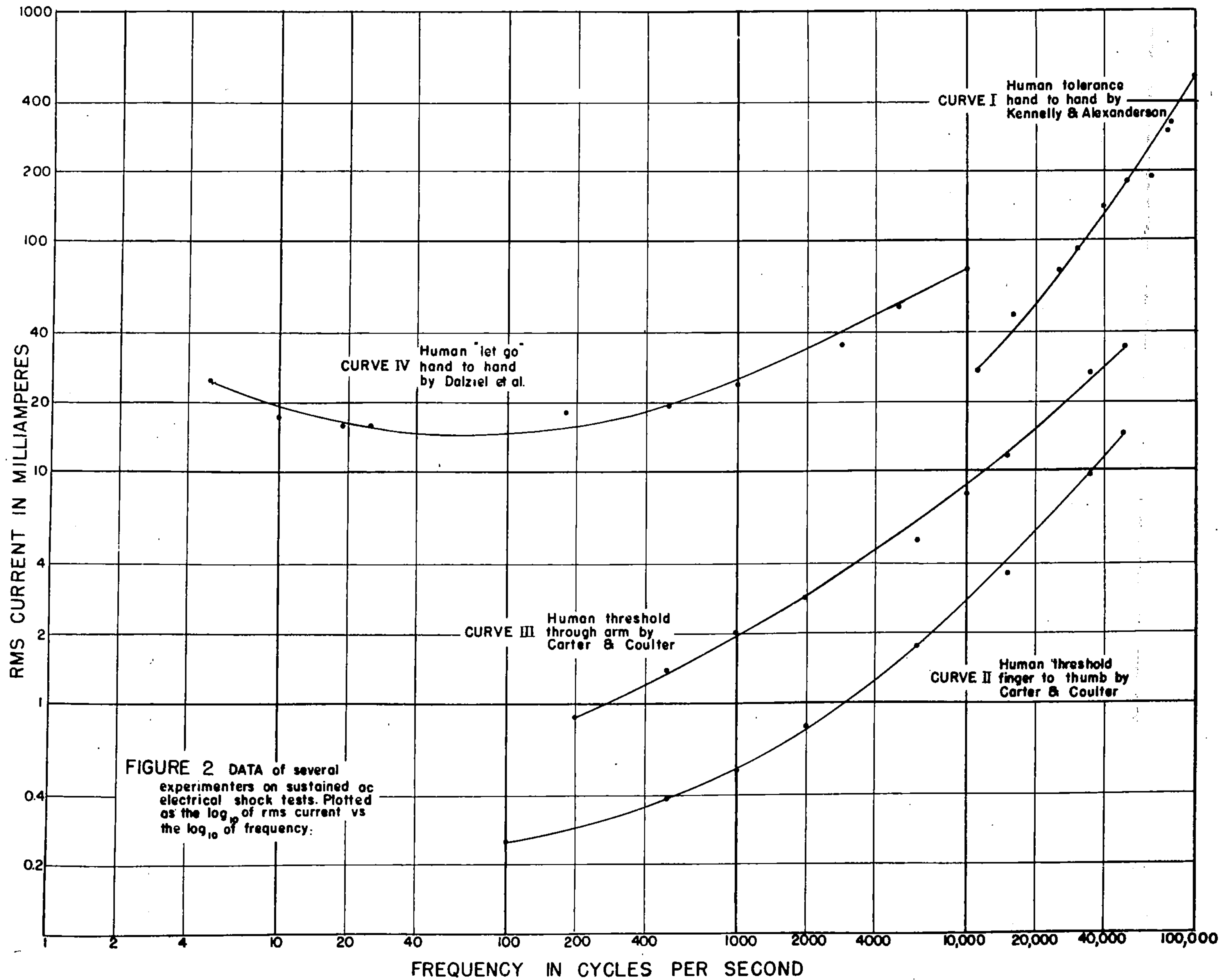

FIGURE 2 DATA of several experimenters on sustained ac electrical shock tests. Plotted as the $\log_{10}$ of rms current vs the $\log_{10}$ of frequency.

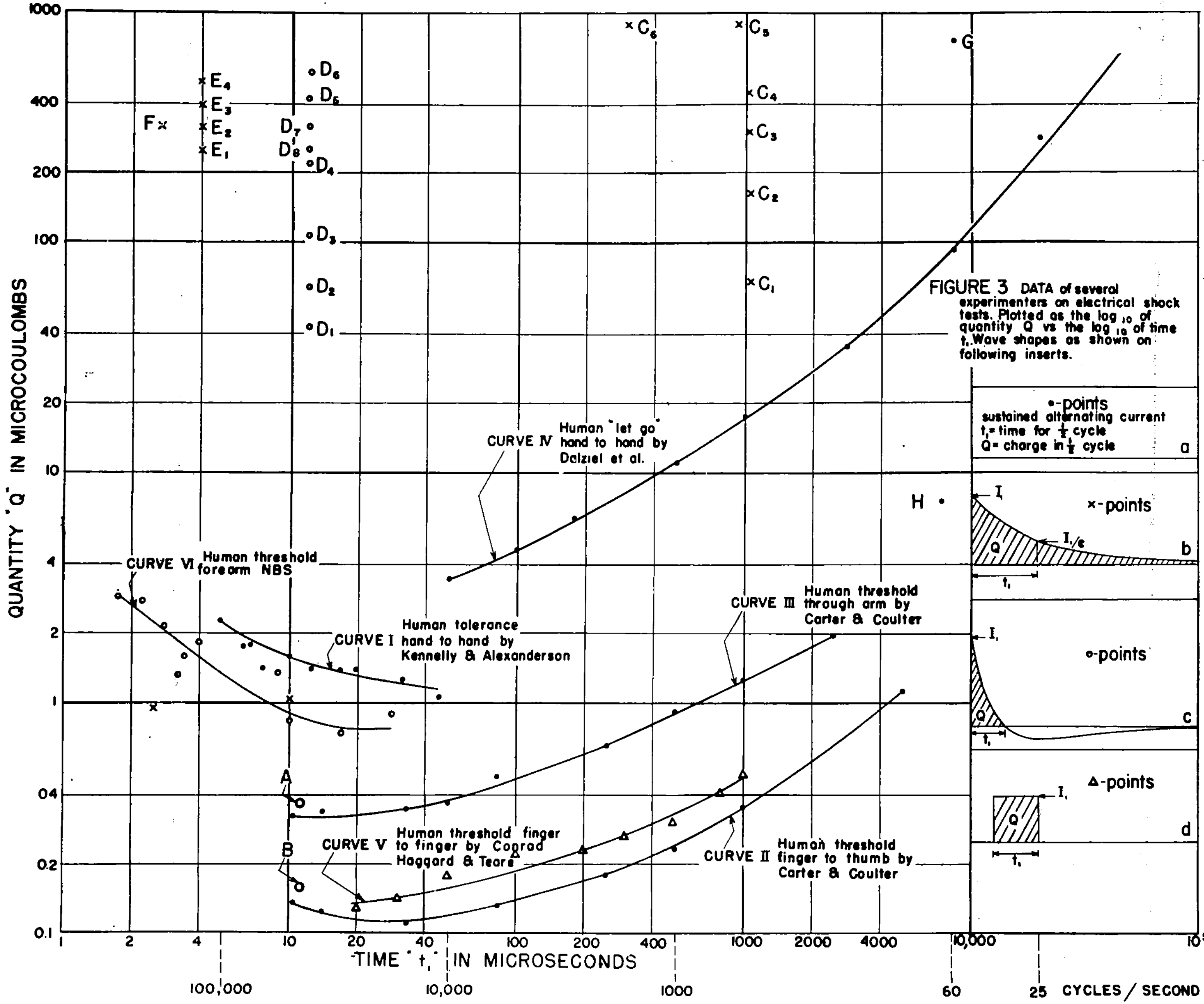

FIGURE 3 DATA of several experimenters on electrical shock tests. Plotted as the $\log_{10}$ of quantity Q vs the $\log_{10}$ of time t_1. Wave shapes as shown on following inserts.

Fig. 3

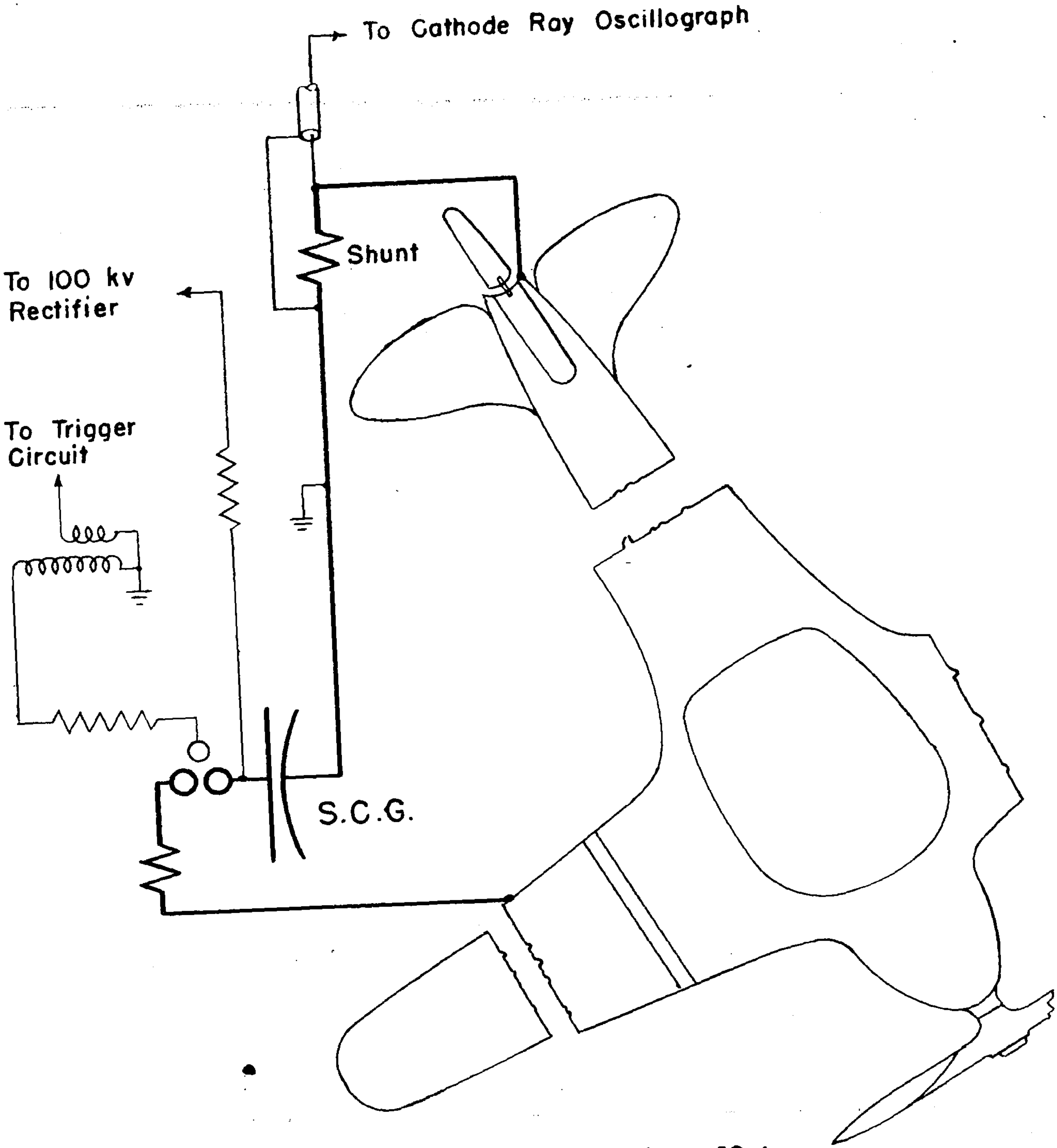

Figure 4.- Schematic diagram of connection of PT 19 A to surge current generator.

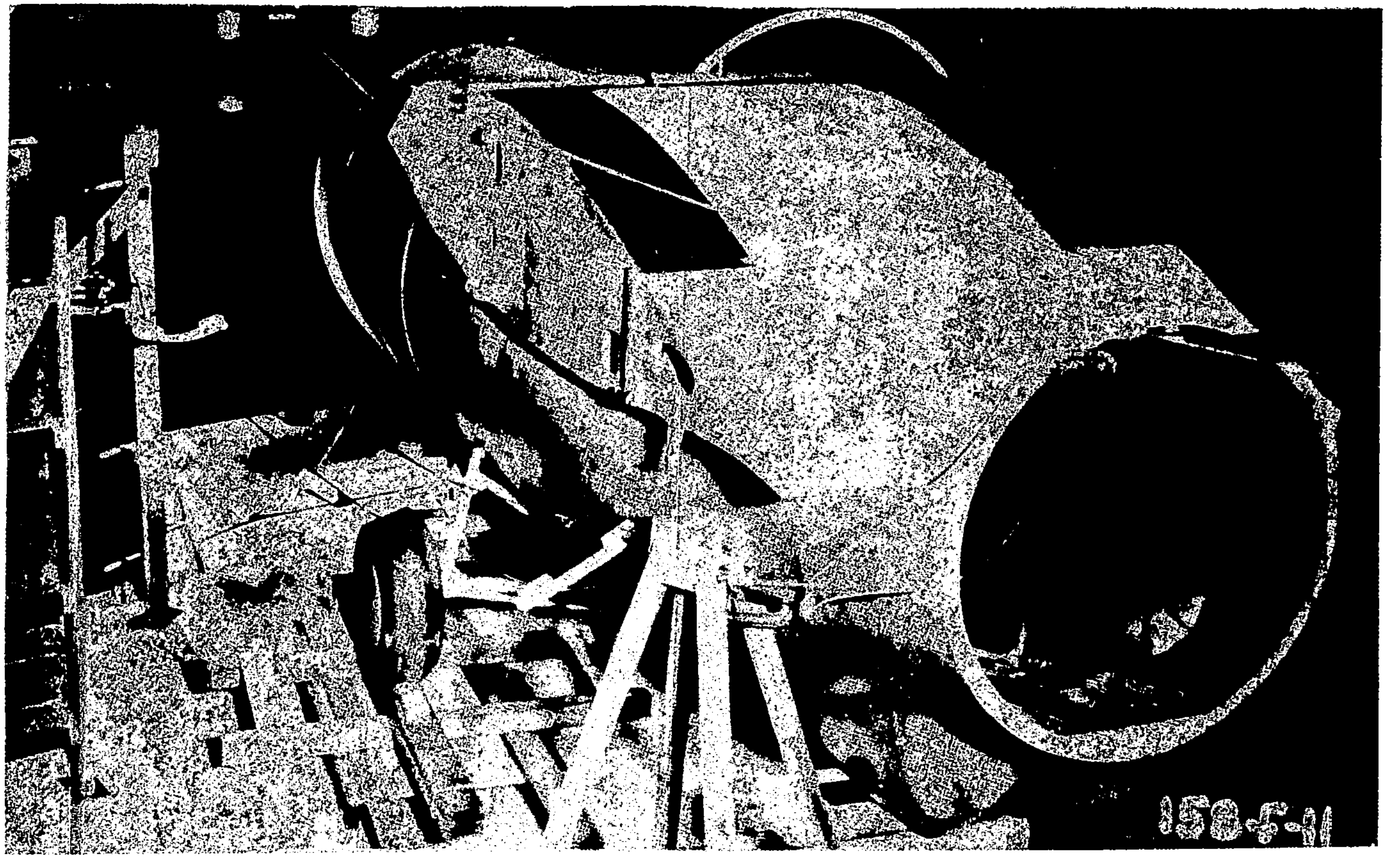

Figure 5.- Fuselage section of glider XCG-7 placed near surge-current generator for surge tests.

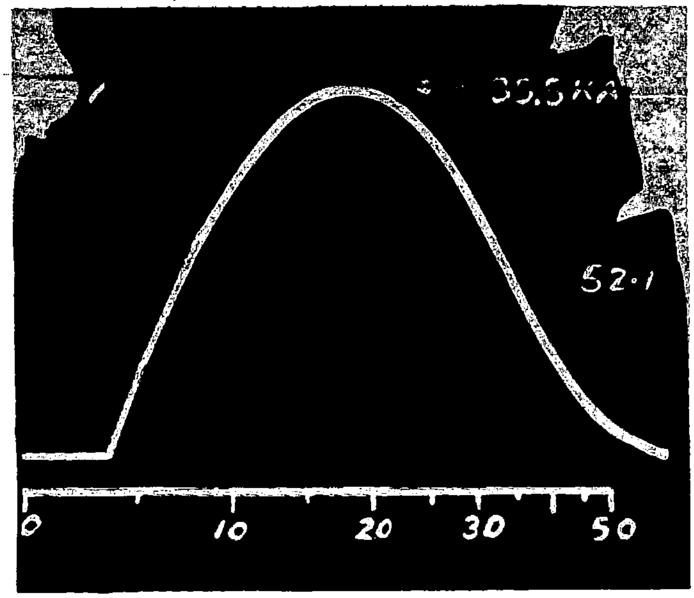

Figure 6.- Oscillogram of discharge current through glider XCG-7. Time scale of abscissas is indicated in microseconds.

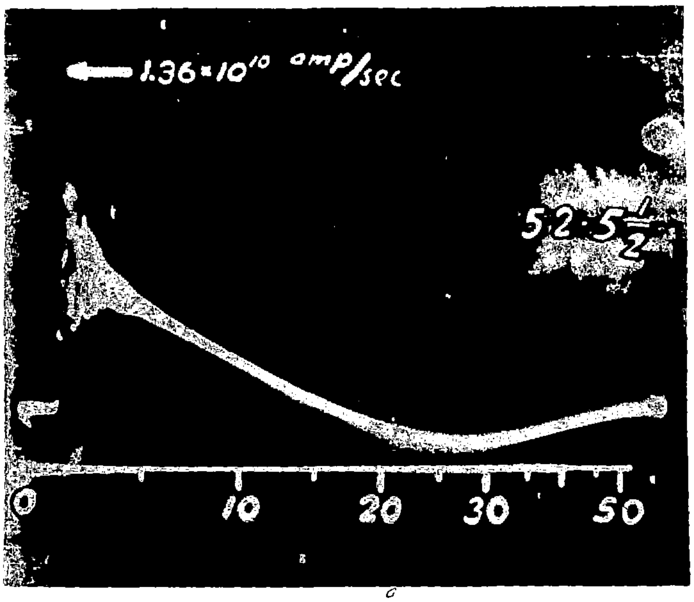

Figure 7.- Oscillogram of rate of change of discharge current through glider XCG-7 (slow sweep on C R O). Time scale is in microseconds.

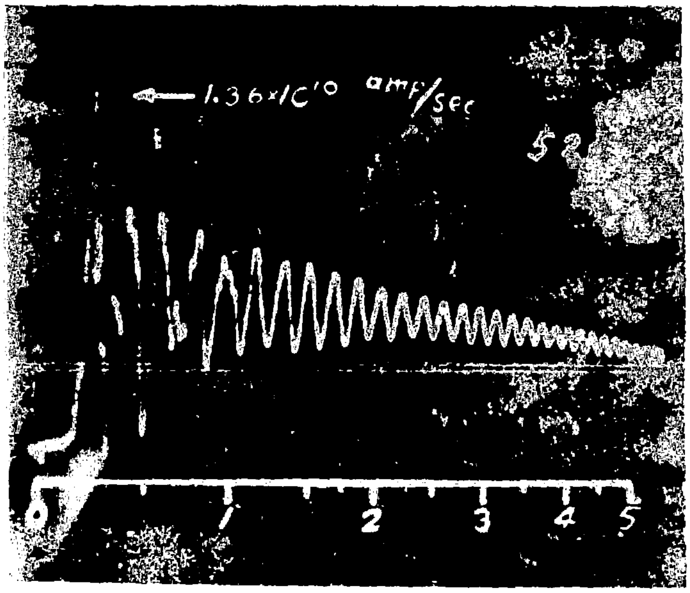

Figure 8.- Initial portion of di/dt as in figure 7 but with faster sweep on oscillograph. Numbers on scale of abscissas show time in microseconds.

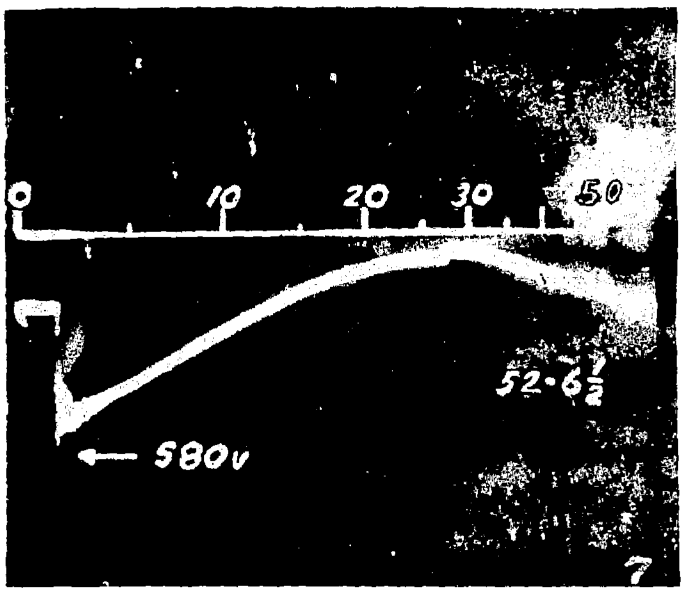

Figure 10.- Oscillogram of induced voltage from "front seat" to "cable release knob" in glider XCG-7. Time is indicated in microseconds. Value is less than shown in column 2 of Table I because of presence of oscillograph cable.

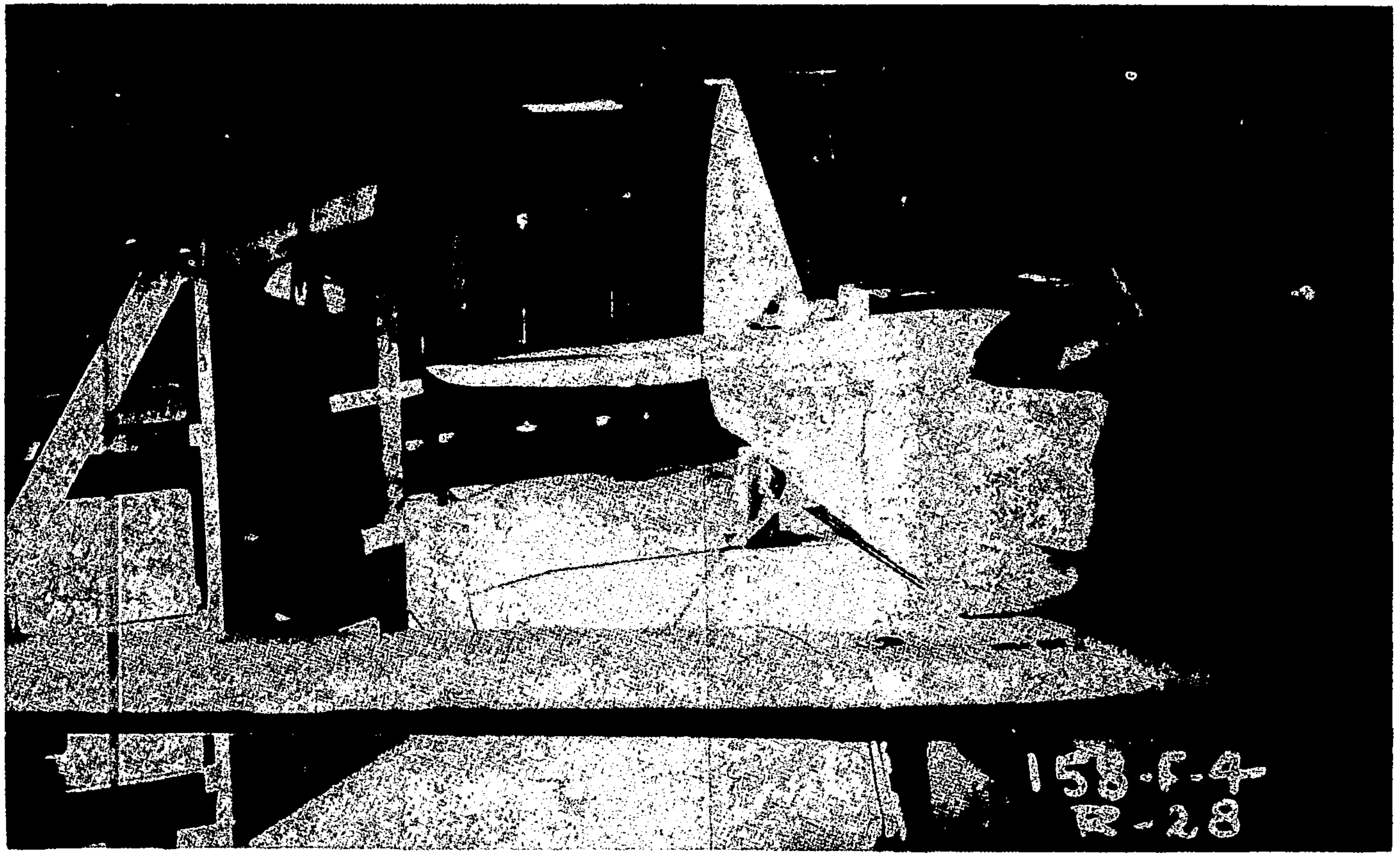

Figure 9.- Fairchild PT19A trainer plane placed near surge-current generator for surge tests. Connections shown are for surge from right wing to tail.

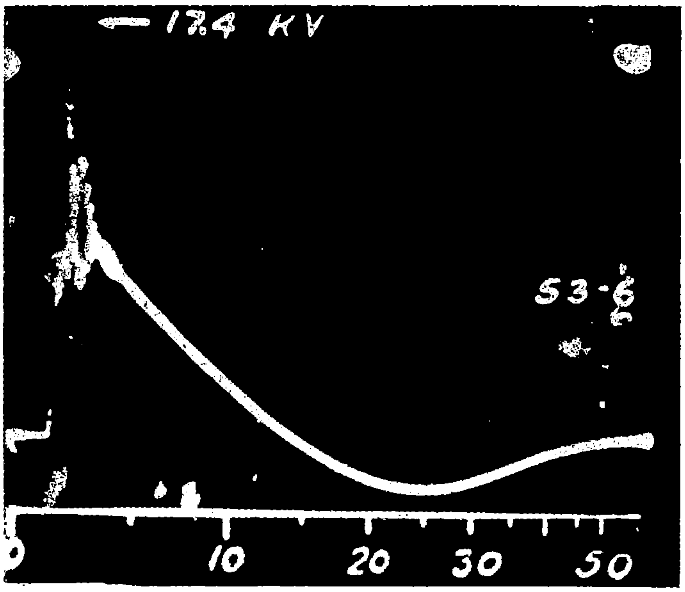

Figure 11.- Oscillogram of induced voltage from nose of glider XCG-7 to rear of main fuselage section. Wire run from measuring cable and divider in nose to rear along the central axis of the glider. Note that voltage exceeded 10,000 volts for several microseconds.

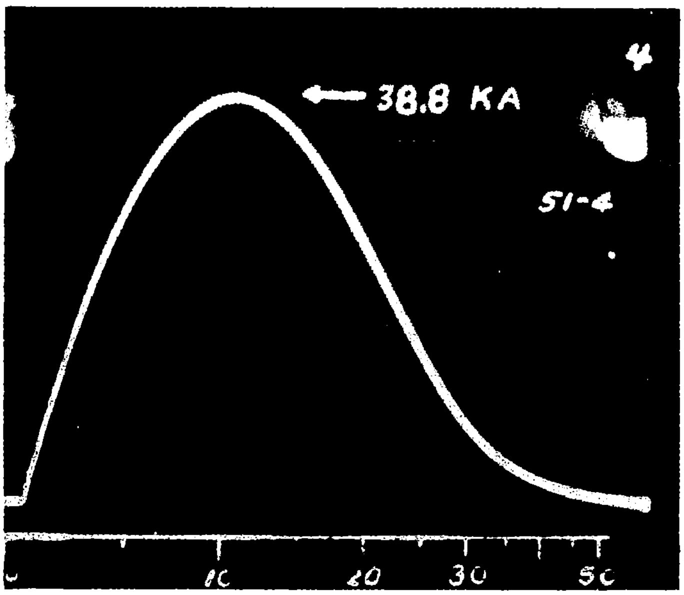

Figure 12.- Oscillogram of discharge current through PT19A wing to wing. Time scale is in microseconds.

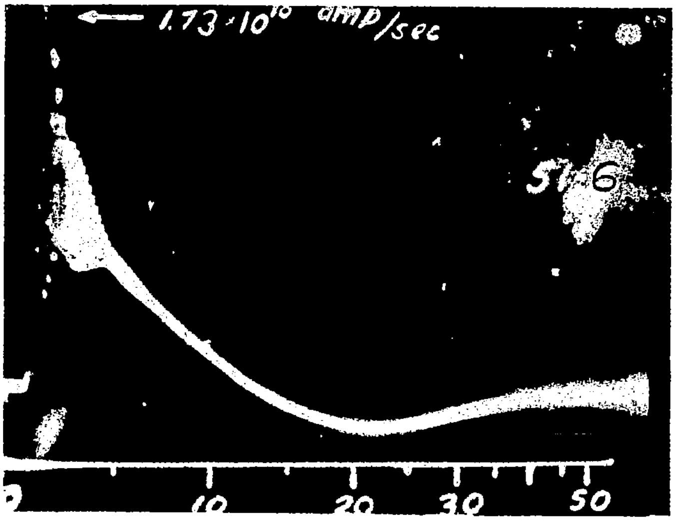

Figure 13.- Oscillogram of rate of change of discharge current through PT19A wing to wing with slow sweep on the oscillograph.

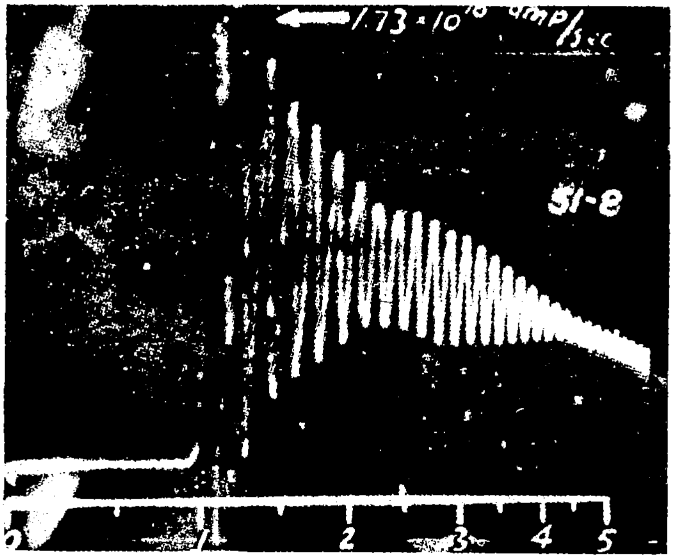

Figure 14.- Same as initial part of figure 13, but with faster sweep on oscillograph. Time scale is indicated in microseconds.

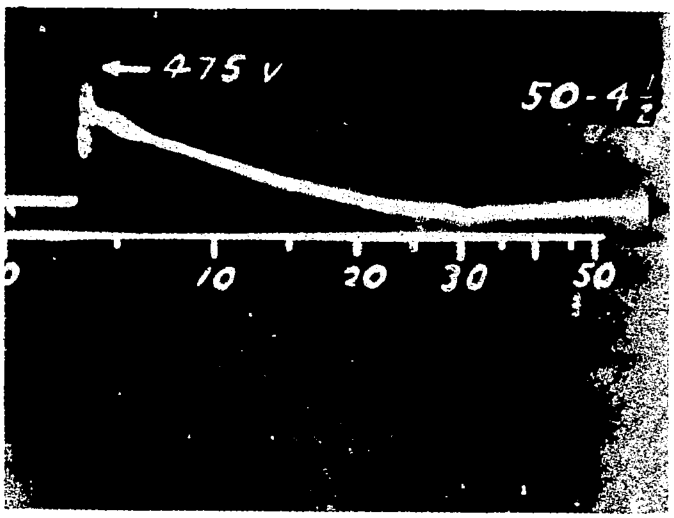

Figure 15.- Oscillogram of induced voltage from rear seat to control stick of PT19A. Main discharge from wing to tail.

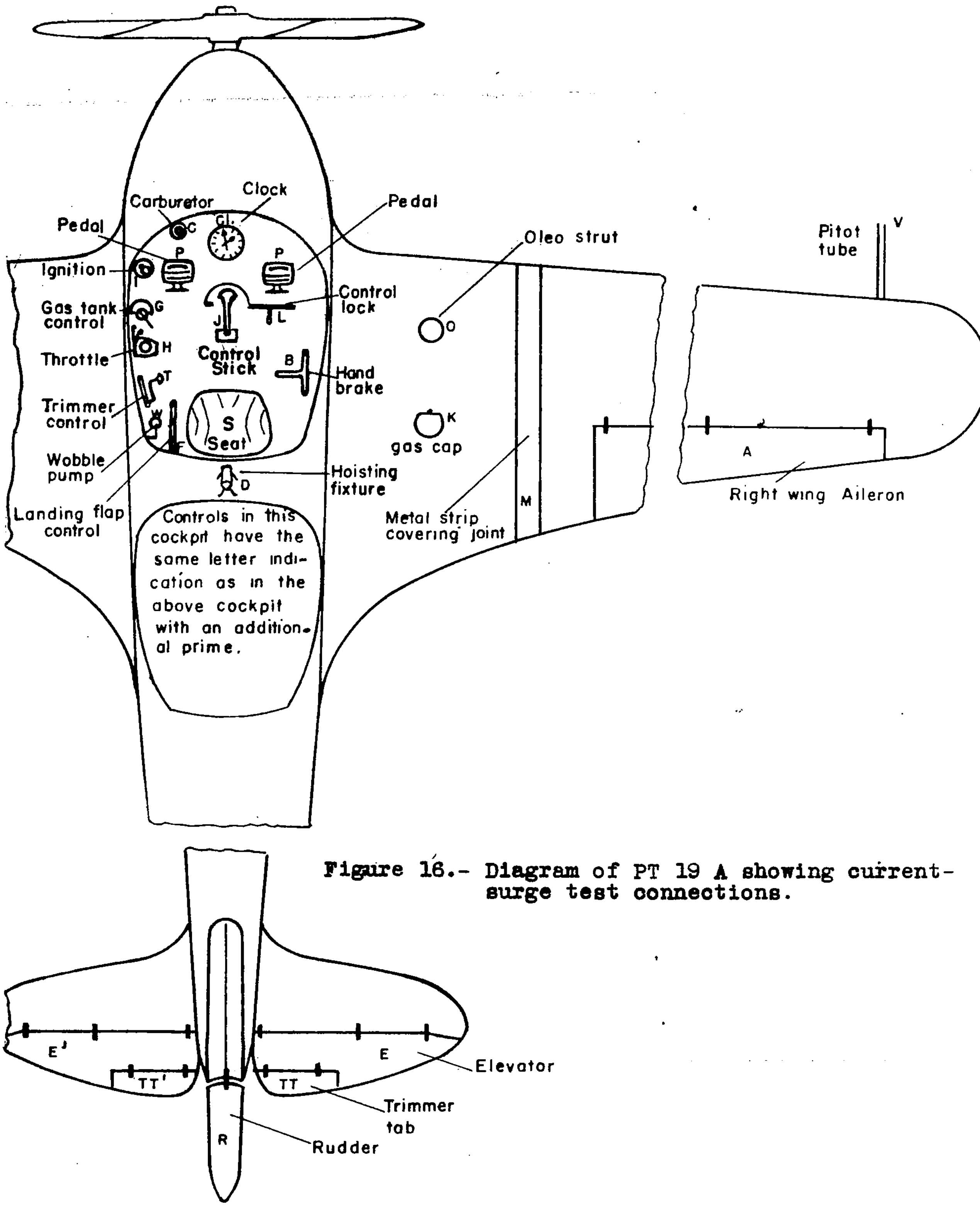

Figure 16.- Diagram of PT 19 A showing current-surge test connections.